# A Rotary-Linear Switched Reluctance Motor for Advanced Industrial Applications

Ioana BENŢIA, Technical University of Cluj-Napoca, Romania, Ioana.Bentia@mae.utcluj.ro
Mircea RUBA, Technical University of Cluj-Napoca, Romania, Mircea.Ruba@mae.utcluj.ro
Loránd SZABÓ, Technical University of Cluj-Napoca, Romania, Lorand.Szabo@mae.utcluj.ro

## Abstract

In the paper a switched reluctance rotary-linear motor is proposed. It is mechanically robust, simple to construct and easy to operate also in hostile working environment. The stator has a modular design compound of three correctly shifted usual 16 poles SRM stators. The rotor is constructed of several common 12 poles SRM rotor stacks. The motor is able to ensure both rotating and linear movement.
The proposed rotary-linear motor machine is expected to be useful in diverse advanced industrial applications where both linear and rotary motion is required and the space at disposal is small (parts assembling systems, component insertion, electrical wiring, etc.).

## 1. Introduction

In modern industrial environment both rotary and linear movements are required. Such applications are the precise parts assembling systems, component insertion machines, electrical wiring equipment, etc.). But in many cases, mainly due to space limitations it is difficult to place two motors to ensure the two types of motion [1]. For such application the rotary-linear motors are the best solutions. Their use is efficient since they do not have complex mechanical structure needing frequent mechanical adjustments. These motors have low manufacturing and maintenance costs at high reliability due to the applied technology [2].

The proposed rotary-linear motor is a direct-driven machine; the mechanical energy is directly transferred to the load. Thus any mechanical couplers (gears or belts) can be eliminated from the motion chain. Other advantages of such motors are their fast response, high flexibility and their drive and control system may be simple.

Switched reluctance motors (SRM) were considered as an unpopular choice for high-precision and high-speed motion applications, because they were difficult to control and their output had high torque ripples. This was due to the fact that the actuator's characteristics were highly dependent on its complex magnetic circuit, which is difficult to model, simulate, and control. But in the recent years a general resurge of interest in the SRMs can be widely observed. This is mostly due to the advancement of power electronics and digital signal processing, and the continuous trend of "simplifying the mechanics through complex control strategy". It must be emphasized that most of these developments were directed mainly towards the rotary SRMs [3]. However also the linear variants of the SRMs were investigated, mainly due to their very simple construction [4].

The paper describes a novel, high performance, direct-driven rotary-linear motion system. The motor is based on the variable reluctance principle [5]. Practically it is an efficient combination of a usual rotational SRM and a special linear SRM having several rotor stacks in its mover. It has all the advantages of the already classical SRMs: mechanical robustness, constructive simplicity and relatively easy control.

The proposed machine aims to replace the traditional rotary-linear systems with a higher performance and lower cost alternative.

In the paper the main structure of the proposed rotary-linear SRM and the sequence of the current pulses for both the rotational and linear movements are given. Also some details on the machine's design algorithm are highlighted. The paper also deals with the two dimensional magnetic field analysis of the machine's the rotational part.

## 2. The proposed rotary-linear SRM

The complex iron core structure of the proposed novel rotary-linear SRM in discussion is given in Fig. 1.

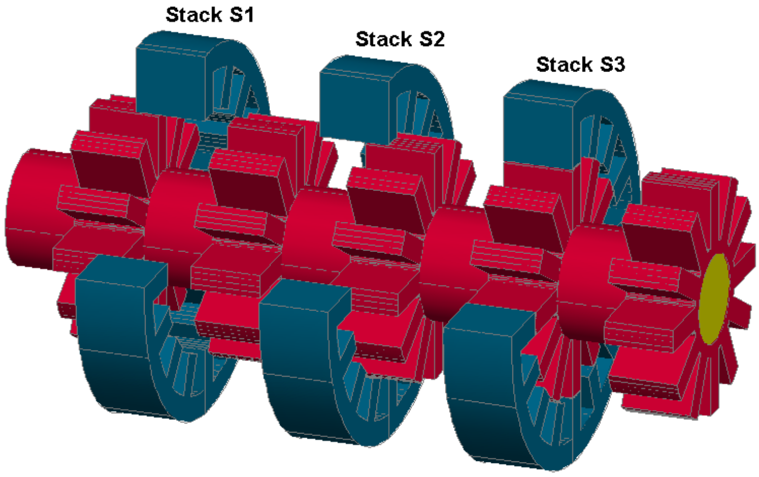


**Fig. 1.** The basic structure of the proposed rotary-linear SRM's iron core

The four-phase stator has a modular design compound of three, correctly shifted, classical 16 poles SRM stators given in Fig. 2.

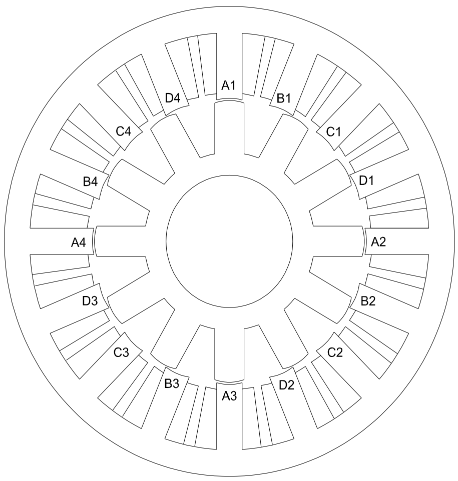


**Fig. 2.** A cross section of the proposed rotary-linear SRM

The rotor is constructed of several common 12 poles SRM rotor stacks. Its structure ensure appropriate flux path along the stators, the air-gap and the rotor. The rotor may rotate and also move on its axial direction.

Due to its specific movement the motor requires also particular bearings. The linear-rotary bearings to be used are designed to permit the shaft to rotate smoothly and with low friction simultaneously during the straight line movement. In such bearings the ball track path is of oval shape (for an infinite ball flow) and both sides of the straight portion of the path are utilized. Two openings in the retainer on the same ball circuit permit balls to contact the shaft and the inner race of the housing in either path, but not at the same time. To ensure the circulation of the balls one of the paths must be loaded and the other one must guarantee the return path of the balls. This special design of the retainers to rotate within the housing and the balls to rotate in any direction allows smooth simultaneous linear and rotary motion [6].

When rotational movement is required four coils on each stator stack are fed function of the rotor posi-

ISBN 978-3-8007-3344-6 © VDE VERLAG GMBH · Berlin · Offenbach 

tion and the imposed current pulses sequence. In Tab. 1 the sequence of the winding's feeding for a clockwise rotation from the initial position shown in Fig. 1 is given.

**Tab. 1.** Sequence of the winding's feeding for the rotating movement

| | Step 1 | | | Step 2 | | | Step 3 | | | Step 4 | | | Step 5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Poles** | **Stack S1** | **Stack S2** | **Stack S3** | **Stack S1** | **Stack S2** | **Stack S3** | **Stack S1** | **Stack S2** | **Stack S3** | **Stack S1** | **Stack S2** | **Stack S3** | **Stack S1** | **Stack S2** | **Stack S3** |
| **A1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| **A2** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| **A3** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| **A4** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| **B1** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **B2** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **B3** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **B4** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **C1** | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **C2** | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **C3** | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **C4** | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **D1** | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| **D2** | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| **D3** | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| **D4** | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |

If linear movement is required the proposed motor will work similarly to a linear SRM [7]. The sequence of the winding's feeding for a linear movement to the right from the initial position seen in Fig. 1 is given in Tab. 2.

**Tab. 2.** Sequence of the winding's feeding for a linear movement

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Step 1** | | | **Step 2** | | | **Step 3** | | | **Step 4** | | |
| **No. of poles** | **Stack S1** | **Stack S2** | **Stack S3** | **Stack S1** | **Stack S2** | **Stack S3** | **Stack S1** | **Stack S2** | **Stack S3** | **Stack S1** | **Stack S2** | **Stack S3** |
| **A1** | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| **A2** | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| **A3** | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| **A4** | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| **B1** | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| **B2** | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| **B3** | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| **B4** | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| **C1** | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| **C2** | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| **C3** | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| **C4** | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| **D1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **D2** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **D3** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **D4** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

ISBN 978-3-8007-3344-6 © VDE VERLAG GMBH · Berlin · Offenbach 

In the case of rotation the stator which has its poles aligned in the axial direction with the rotor poles will develop most of the torque. The other two stator stacks will also contribute to the rotational movement. As they are symmetrically unaligned on the axial direction the axial forces developed by them will be equal but of opposite direction, hence their sum will be nil and no linear movement will be produced.

When linear displacement is imposed almost all the phases of one module will be fed (excepting the coils on the completely unaligned stator poles). The rotor stack will be aligned upon the variable reluctance principle with the energized coils stator's poles.

Each of the totally 12 phases are connected to a half H-bridge power converter. The phase currents are controlled by means of pulse-width modulation (PWM) techniques [8].

## 3. The design of the rotary-linear SRM

The design of the rotary-linear SRM in discussion follows the classical steps for the rotary and linear SRMs [9].

The sizing of the SRM is started by imposing the:

i.) rated voltage and current ($U_N$, $I_N$),

ii.) the number of phases and stator stacks ($m$, $N_{st}$),

iii.) the machine's rated power ($P_{2N}$),

iv.) the air-gap ($g$)

v.) the air-gap flux density in aligned position ($B_{g_{\max}}$),

vi.) the rated speed, torque and efficiency ($n_N$, $T_N$, $\eta_N$)

The design in general terms follows the usual algorithm used for SRMs. Due to lack of space here only the key equations are given.

The design starts with the computation of the machine's mean diameter, measured in the middle of the air-gap [2]:

$$D_g = \sqrt[3]{\frac{P_{2N} \cdot Q_s \cdot k_\sigma}{Q_R \cdot \pi^2 \cdot \eta_N \cdot k_L \cdot \frac{n_N}{60} \cdot B_{g\max} \cdot \left(1 - \frac{1}{K_{cr}}\right) \cdot A_s}} \tag{1}$$

where $Q_S$ and $Q_R$ are the number of stator and rotor poles. The $k_\sigma$ and $k_L$ are the leakage flux factor, respectively the aspect factor. $A_s$ is the stator's electrical loading.

In this stage of the design the flux densities in different regions of the machine must be imposed. This is one of the key issues during the machine's sizing.

Next the main dimensions of the stator and rotor cores, respectively of the coils have to be calculated.

A specific attention should be given to the selection of the machine's aspect since the active length of the stack imposes the step length during the linear movement.

The torque to be developed by the machine is given by:

$$T = \frac{P_{2N}}{2\pi \frac{n_N}{60}} \tag{2}$$

After finishing sizing a single stack of the rotary-linear SRM the flux densities in the machine must be checked either applying the equivalent magnetic circuit approach, or by means of finite element method (FEM) based numeric field computations.

As the linear movement of the machine is concerned, two main dimensions must be calculated. The linear pole pitch ($t_d$) is computed by considering the distance between the rotor stacks equal to the length of the stator and rotor stacks, respectively.

The distance between the axes of two neighbored stator stacks can be calculated by using:

$$I_x = k\, t_d + \left(\frac{t_d}{3}\right) \qquad \begin{matrix} k \in N \\ k \geq 2 \end{matrix} \tag{3}$$

The losses in the machine can also be computed or analytically or by using field computations [10]. Finally the thermal analysis of the machine has to be performed.

Using the developed design algorithm a sample motor was sized for the following input data: $N_{st}$ = 3, m = 3, $P_{2N}$ = 350 W, $n_N$ = 600 r/min, $T_N$ = 5.5 N·m, $\eta_N$ = 0.85, $U_N$ = 300 V (all for the rotational part).

# 4. Field computations

The numeric field analysis performed upon the finite element method (FEM) is the best choice to validate of the machine's design [11]. The Flux 2D program package was used for this purpose. Both static and transient analysis was performed for verifying the rotational part of the designed rotary-linear SRM.

The flux lines inside the machine and the corresponding flux density color map for a certain position of the rotational part of the machine in discussion id given in Fig. 3.

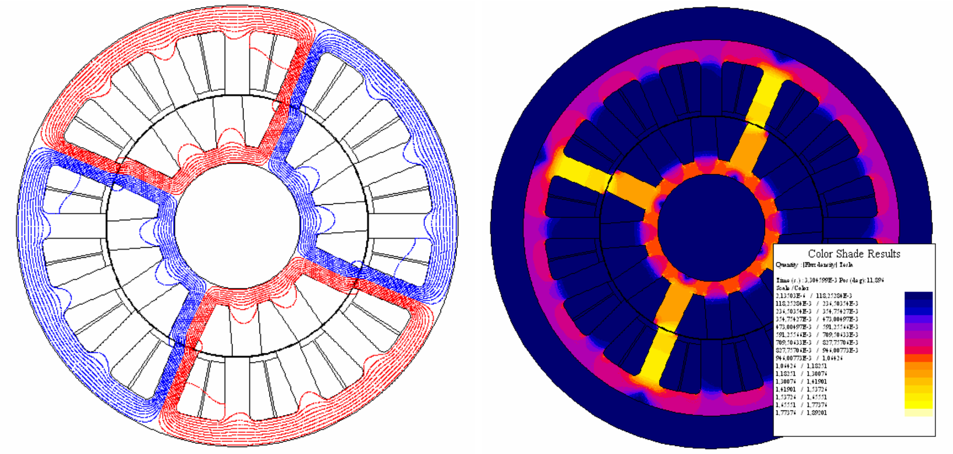


**Fig. 3.** The flux lines and the color map of the flux density for the rotational part of the machine

As it can be seen both the flux distribution and the flux density values inside the machine are in accordance the expectations.

The dynamic behavior of the rotational part of the machine was studied using co-simulation techniques by coupling Flux 2D field computation program with the Matlab/Simulink environment [12]. This way both the SRM and its power converter are simulated. In Fig. 4 the four phase currents, respectively the developed torque versus time plots are given.

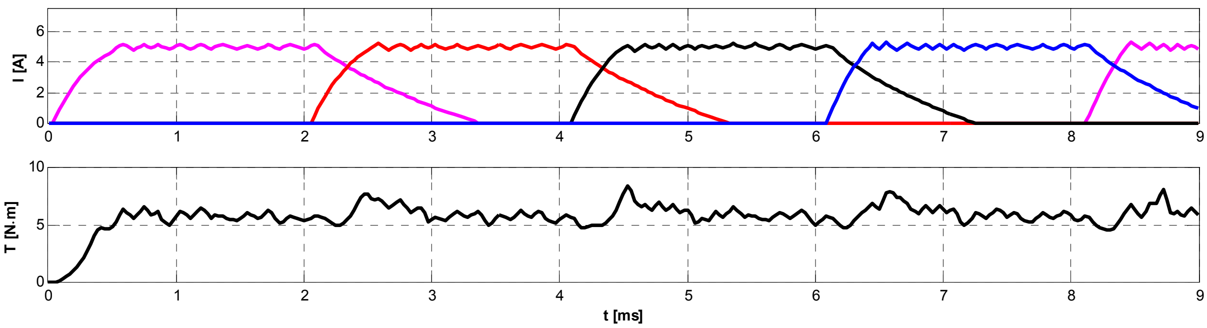


**Fig. 4.** The results of the dynamic analysis of the machine

Also the dynamic performances of the rotational part of the linear-rotary SRM are as they were expected during the analytical computations. By improving the control strategy of this part of the machine the torque ripples can be further reduced.

## 5. Conclusions

The combination of a rotary and a linear movement on the same axis is frequently required in diverse industrial systems. For such applications the proposed rotary-linear motor seems to be an excellent solution.

The two dimensional magnetic field analyses emphasized the correct design of the machine's rotational part. As during the linear movement of the machine the magnetic flux has an actually three dimensional path obligatory a 3D FEM analysis should be performed, which will be the immediate next step in the study of the proposed rotary-linear SRM.

To work out the complicated control of the well-coordinated compound movement of the machine the static characteristics will be computed. These will be integrated as look-up tables in the SIMULINK program simulating the complex behavior of the machine.

## 6. Acknowledgment

This paper was supported by the project "*Doctoral studies in engineering sciences for developing the knowledge based society – SIDOC"* contract no. POSDRU/88/1.5/S/60078, project co-funded from European Social Fund through Sectorial Operational Program Human Resources 2007-2013.

## 7. Literature

[1] Benţia, I., Szabó, L.: Rotary-Linear Machines – A Survey, Journal of Computer Science and Control Systems, vol. 3, no. 2, 2010, pp. 11-14.

[2] Krishnan R.: Switched Reluctance Motor Drives – Modeling, Simulation, Analysis, Design, and Applications. Industrial Electronics Series, CRC Press, Boca Raton (USA), 2001.

[3] Pan, J.F., Cheung, N.C., Cao, G.: A Rotary-Linear Switched Reluctance Motor, Proceedings of the 3rd International Conference on Power Electronics Systems and Applications (PESA '2009), pp. 1-4.

[4] Viorel, I.A., Szabó L., Kovács Z.: On the Switched Reluctance Linear Motor Positioning System Control, Proceedings of the International Conference on Power Electronics, Drives and Motion (PCIM '98), Nürnberg (Germany), 1998, vol. Intelligent Motion, pp. 21-30.

[5] Henneberger, G., Viorel, I.A.: Variable reluctance electrical machines, Shaker Verlag, Aachen (Germany), 2001.

[6] The Revolutionary Ball Bearing that Combines Unlimited Linear and Rotary Motion, Linear Rotary Bearings, Inc., Bedford Hills (NY, USA). URL: http://www.e-lrb.com/pdf/LRB_CATALOG.pdf.

[7] Viorel, I.A., Szabó L., Strete L.: Speed-thrust Control of a Double Sided Linear Switched Reluctance Motor (DSL-SRM), Proceedings of the 18th International Conference on Electrical Machines (ICEM '2008), 2008, Vilamoura (Portugal), on CD.

[8] Miller, T.J.E. (ed.): Electronic Control of Switched Reluctance Machines. Technology & Engineering Series, Newnes, Oxford (UK), 2001.

[9] Krishnan, R., Arumugan, R., Lindsay, J.: Design procedure for switched-reluctance motors. IEEE Transactions on Industry Applications, vol. 24, no. 3, pp. 456-461.

[10] Byeong-Seok, L., Han-Kyung, B., Vijayraghavan, P., Krishnan, R.: Design of a linear switched reluctance machine. IEEE Transactions on Industry Applications, vol. 36, no. 6, pp. 1571-1580.

[11] Bauer, P., van Duijsen P.J.: Challenges and Advances in Simulation, Proceedings of the 36th Annual IEEE Power Electronic Specialists Conference (PESC '05), Recife (Brazil), 2005, pp. 1030-1036.

[12] Szabó, L., Ruba, M.: Using Cosimulations in Fault Tolerant Machine's Study, Proceedings of the 23rd European Conference on Modelling and Simulation (ECMS '2009), Madrid (Spain), 2009, pp. 756-762.